Grid integration of variable renewable energy

Technical fundamentals of PV power generation

Albrecht Tiedemann (RENAC)

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About Albrecht Tiedemann

- Since 2009: Renewables Academy (RENAC) AG; Head of grid integration / energy policy and wind energy division; Lecturer for training programs on grid integration of renewable energy and wind energy, capacity building programs and the E-learning platform RENAC-Online

- 2003 – 2009: German Energy Agency; Project manager for grid integration of renewable energy and onshore / offshore wind energy; Chairman of the German Offshore Committee
- 1989 – 2003: Federal Environmental Agency; Scientific assistant for offshore wind energy, offshore gas / oil exploration, pulp and paper industry, life cycle assessment
- 1989: Graduated as Engineer Environmental Protection Technology at Technical University of Berlin

Learning objectives of the entire training 1/2

- A participant who has met the objectives of the course will be able to develop an interactive training session to
- Determine effects of integrating higher shares of RTS into the distribution network.
- Understand photovoltaic technology fundamentals with regard to grid integration (session 1)
  - From DC to AC - introduction to PV inverter technology
  - Effect of temperature and irradiation on DC voltage
  - MPP-tracking
- Explain voltage control concepts with PV (session 2)
  - Static and dynamic voltage control with grid connected PV
  - Grid code requirements overview

Learning objectives of the entire training 2/2

- A participant who has met the objectives of the course will be able to develop an interactive training session to
  - Explain PV short-term power forecasts for distribution grids (session 3)
    - Statistical and physical models
    - Forecast error
    - Forecast implementation group work
  - Explain frequency control with PV (session 4)
    - Residual load approach
    - Combine different distribution functions of imbalances
    - Use a probabilistic balancing power calculation tool to calculate the amount of positive and negative balancing power needed to ensure a certain system reliability

Learning objectives

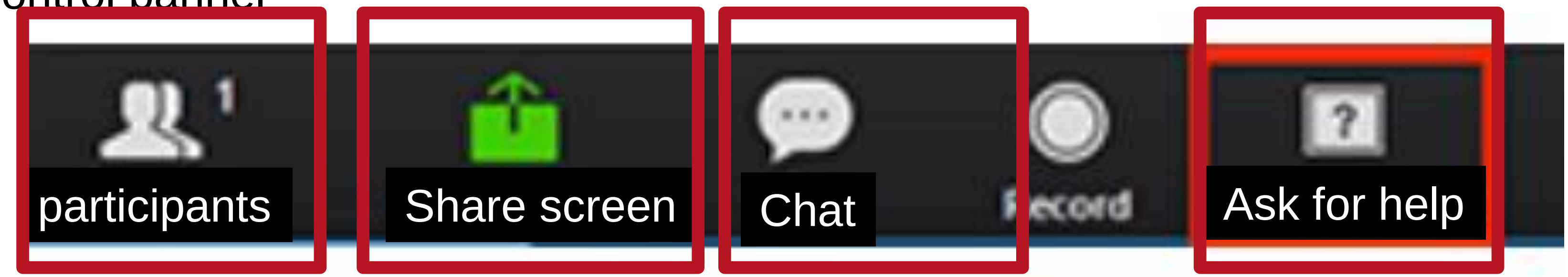
Interactive virtual classroom with breakout rooms for group work

For this training session

1. Lecture in the ***virtual classroom*** with all paricipants
2. The participants will move to ***breakout rooms*** for group exercise
   - Solve the exercises in your group
   - Use the whiteboard, use the chat
   - Don‘t forget fo SAVE your results!
   - Every group chooses a presenter who presents the results in the classroom (share your screen)
3. The breakout rooms will end after a certain time and you will atomatically be in the ***virtuall classroom*** again
   - Participants present results in the virtual classroom with all paricipants
   - Discussion of results

Breakout room tools

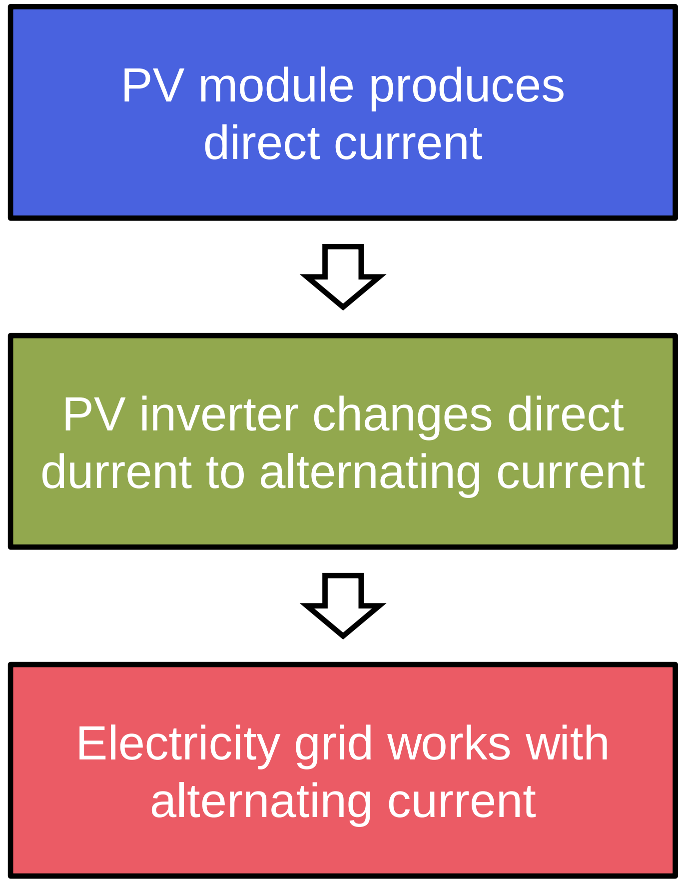
- Control pannel



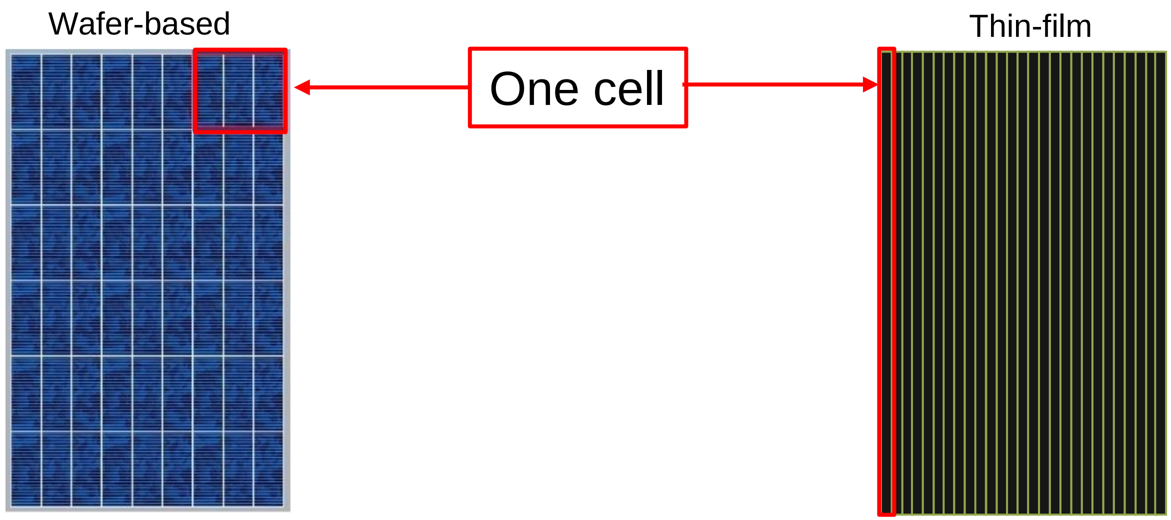
- Whiteboard

Photovoltaic inverter technology – from DC to AC

Photovoltaic - from direct current to alternating current



Wafer based and thin fim PV modules



- Silicon wafers are processed to solar cells which are then connected in series
- Current module efficiencies: 16-24%
- Proven technology: high market share
- Potential for low cost high efficiency (20 - 30%)

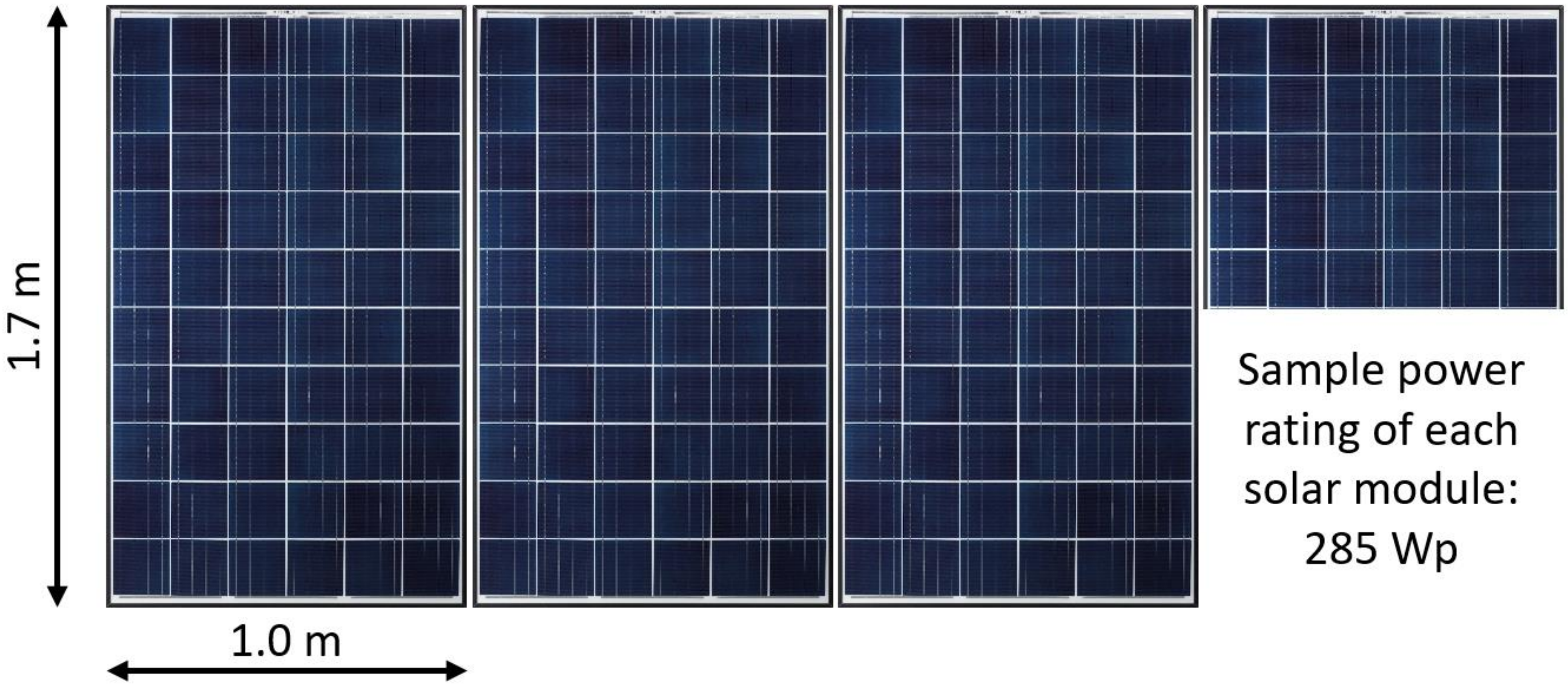
- Depositions on large area substrates and ‘monolithic series integration’ of the cells (typically by lasing)
- Current module efficiency 11-19%
- Proven technology but low market share
- Potential for ultra-low cost and medium efficiency (15-25%)

1: *Photovoltaik report by Fraunhofer ISE, 12. July 2017*

Power of a PV module

- Name plate information about electrical ratings of PV modules (e.g. power, MPP currents and voltages, etc.) is measured at the internationally acknowledged Standard Test Conditions (STC):
  - Cell temperature: 25°C
  - Irradiance: 1,000 W/m²
- W_p (Watt peak) indicates the nominal power output of a solar cell or PV module at STC
  - Power P [W] = Current I [A] x Voltage V [V]
- Power output of PV modules depend i.a. on
  - cell material
  - temperature and
  - Irradiance

What is 1 kWp (kiloWatt peak)?



Sample power rating of each solar module: 285 Wp

Exercise: What is the installed capacity of this rooftop PV system have (each module has 250 Wp)?

PV farm, from modules to central inverter

Module

DC-cables

DC main box

DC main box in/out

DC fuses

Central inverter, DC in , AC out

Datasheet of solar module sample 1/2

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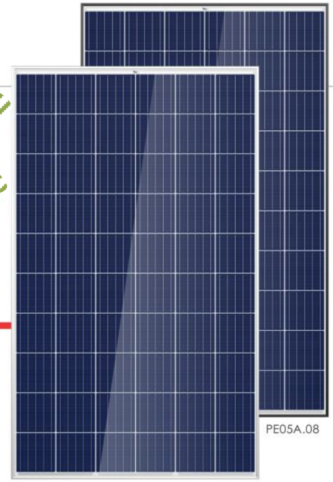
Mono Multi Solutions



1500V MODULE

60 CELL
MULTICRYSTALLINE MODULE

260-270W
POWER OUTPUT RANGE

16.5%
MAXIMUM EFFICIENCY

0~+5W
POSITIVE POWER TOLERANCE

As a leading global manufacturer of next generation photovoltaic products, we believe close cooperation with our partners is critical to success. With local presence around the globe, Trina is able to provide exceptional service to each customer in each market and supplement our innovative, reliable products with the backing of Trina as a strong, bankable partner. We are committed to building strategic, mutually beneficial collaboration with installers, developers, distributors and other partners as the backbone of our shared success in driving Smart Energy Together.

Ideal for large scale installations
- High power footprint reduces installation time and BOS costs
- UL1500V/IEC1500V certified

One of the industry's most trusted modules
- Field proven performance

Highly reliable due to stringent quality control
- Over 30 in-house tests (UV, TC, HF, and many more)
- In-house testing goes well beyond certification requirements
- PID resistant
- 100% EL double inspection

Certified to withstand challenging environmental conditions
- 2400 Pa wind load
- 5400 Pa snow load
- 35 mm hail stones at 97km/h

LINEAR PERFORMANCE WARRANTY

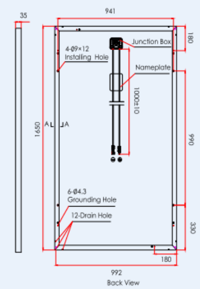
10 Year Product Warranty · 25 Year Linear Power Warranty

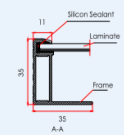
Comprehensive products and system certificates
- IEC 61215/ IEC 61730/ UL 1703/ IEC 61701/IEC 62716
- ISO 9001: Quality Management System
- ISO 14001: Environmental Management System
- ISO 14064: Greenhouse Gases Emissions Verification
- OHSAS 18001: Occupation Health and Safety Management System

1500V MODULE TSM-PE05A/TSM-PE05A.08

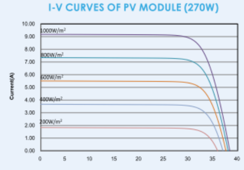
PRODUCTS	POWER RANGE
TSM-PE05A	260-270W
TSM-PE05A.08	260-270W

DIMENSIONS OF PV MODULE unit:mm

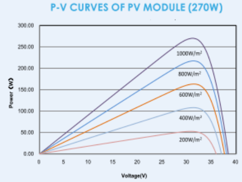




I-V CURVES OF PV MODULE (270W)



P-V CURVES OF PV MODULE (270W)



ELECTRICAL DATA (STC)			
Peak Power Watts-P_{MAX} (Wp)*	260	265	270
Power Output Tolerance-P_{MAX} (W)		0 ~ +5	
Maximum Power Voltage-V_{MPP} (V)	30.6	30.8	30.9
Maximum Power Current-I_{MPP} (A)	8.50	8.61	8.73
Open Circuit Voltage-V_{OC} (V)	38.2	38.3	38.4
Short Circuit Current-I_{SC} (A)	9.00	9.10	9.18
Module Efficiency η_m (%)	15.9	16.2	16.5

STC: Irradiance 1000 W/m², Cell Temperature 25°C, Air Mass AM1.5.
*Measuring tolerance: ±3%.

ELECTRICAL DATA (NOCT)			
Maximum Power-P_{MAX} (Wp)	193	197	200
Maximum Power Voltage-V_{MPP} (V)	28.4	28.6	28.7
Maximum Power Current-I_{MPP} (A)	6.81	6.89	6.97
Open Circuit Voltage-V_{OC} (V)	35.4	35.5	35.5
Short Circuit Current-I_{SC} (A)	7.27	7.35	7.41

NOCT: Irradiance at 800 W/m², Ambient Temperature 20°C, Wind Speed 1 m/s.

MECHANICAL DATA	
Solar Cells	Multicrystalline 156 × 156 mm (6 inches)
Cell Orientation	60 cells (6 × 10)
Module Dimensions	1650 × 992 × 35 mm (65.0 x 39.1 x 1.38 inches)
Weight	18.6 kg (41.0 lb)
Glass	3.2 mm (0.13 inches), High Transmission, AR Coated Tempered Glass
Backsheet	White
Frame	Silver Anodized Aluminium Alloy (PE05A); Black (PE05A.08)
J-Box	IP 67 or IP 68 rated
Cables	Photovoltaic Technology Cable 4.0mm² (0.006 inches²), 1000 mm (39.4 inches)
Connector	MC4(1500V)

TEMPERATURE RATINGS	
Nominal Operating Cell Temperature (NOCT)	44°C (±2°C)
Temperature Coefficient of P_{MAX}	- 0.41%/°C
Temperature Coefficient of V_{OC}	- 0.32%/°C
Temperature Coefficient of I_{SC}	0.05%/°C

MAXIMUM RATINGS	
Operational Temperature	-40~+85°C
Maximum System Voltage	1500V DC (IEC) 1500V DC (UL)
Max Series Fuse Rating	15A

WARRANTY
- 10 year Product Workmanship Warranty
- 25 year Linear Power Warranty

(Please refer to product warranty for details)

PACKAGING CONFIGURATION
- Modules per box: 30 pieces
- Modules per 40' container: 840 pieces

TSM_EN_2016_A

CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT.

Source: Trina Solar

Datasheet of solar module sample 2/2

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Source: Trina Allmax TSM-280

Important datasheet information for grid integration (P-V curve and I-V curve)

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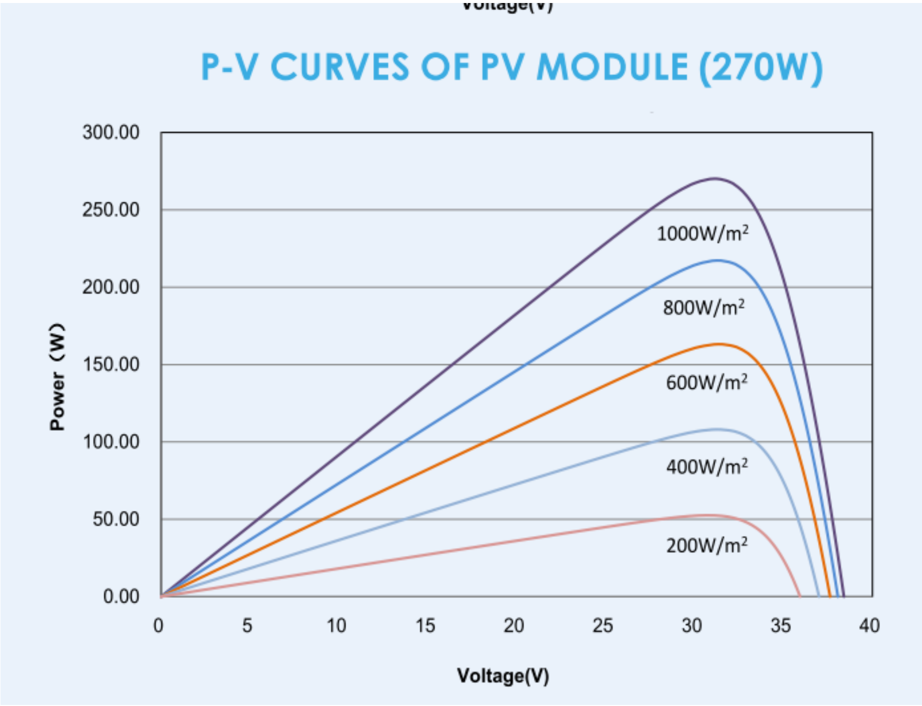

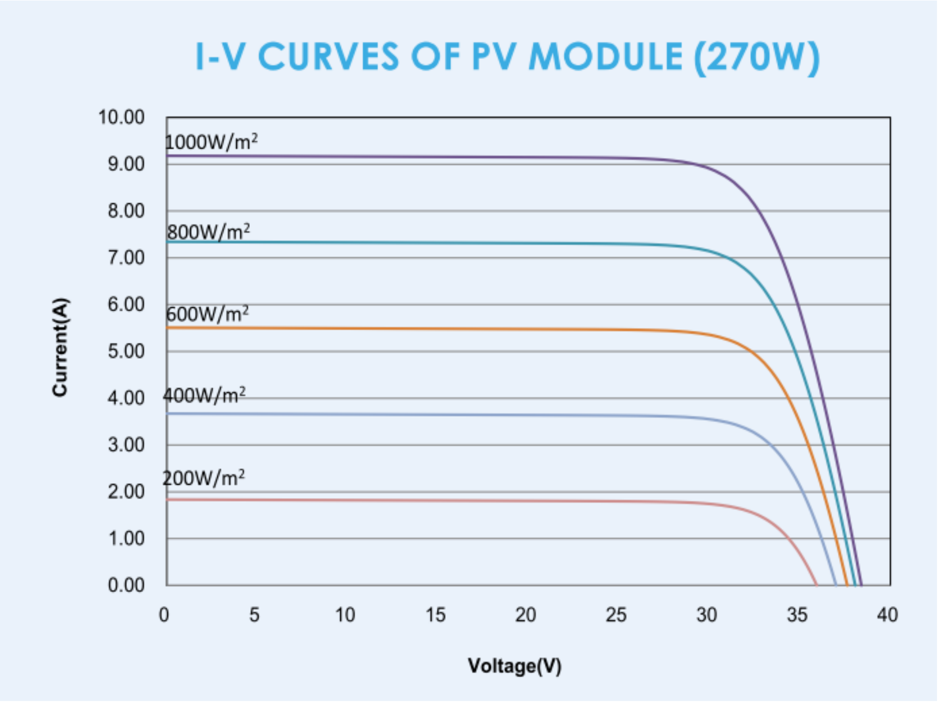

- P - V curve = Power – Voltage curve
- I - V curve = Current – Voltage curve

Source: Trina Allmax TSM-280

- How does an inverter look like?

String inverter

Central inverter

Source: REFUSol GmbH, SMA Solar Technology AG

- Micro inverter

Technical data of micro, string and central inverters

Typical values	String inverter	Central inverter
DC-Input power		
DC-Voltage range		
DC-Current range		
Efficiency		
MPPTs		
Phases		
Grid voltage level		

V = Voltage, Wp = Watt peak, MPPT = Maximum Power Point Tracker

Pictures: SMA Solar Power Techology SA

Technical data of micro, string and central inverters

Typical values	String inverter	Central inverter
DC-Input power	1…100 kWp	100…2500 kWp
DC-Voltage range	<≈ 1000 V	<≈ 1500 V
DC-Current range	<≈ 100 A	<≈ 2000 A
Efficiency	<≈ 98%	<≈ 99%
MPPTs	1…5	1
Phases	1 or 3	3
Grid voltage level	low voltage grid	medium voltage grid

V = Voltage, Wp = Watt peak, MPPT = Maximum Power Point Tracker

Pictures: SMA Solar Power Techology SA

Centralized or decentralized inverter systems?

	Decentralized (micro/string inverter)	Centralized (central inverter)
Recommended plant size		
Advantages		
Dis-advantages		

Centralized or decentralized inverter systems?

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	Decentralized (micro/string inverter)	Centralized (central inverter)
Recommended plant size	1…1000 kWp	>≈ 500 kWp
Advantages	• flexible system design / expansion • Less DC-wiring/switchgear • simple logistics • lower mismatching losses (multiple MPPTs) • easy O&M (“replacement”) • lower vulnerability / downtime	• lower price • higher yield (lower self-consumption, higher efficiency) • faster dynamic control • easier to update • clearer setup • simpler communication • faster commissioning
Dis-advantages	• higher price • lower efficiency • complex system setup	• needs higher logistical effort • higher vulnerability / downtime • higher O&M cost

Question: Who collects information about the inverters connected to your distribution grid?

	Responsible institution(s)
Date of commissioning	Who is responsible or should be responsible to collect information about the inverters connected to your distribution grid?
Capacity	
Status of operation	
Grid code compliance	
Operator	
Location	

Pictures: SMA Solar Technology AG

Pictures: SMA Solar Power Techology SA

Market Data Register in Germany

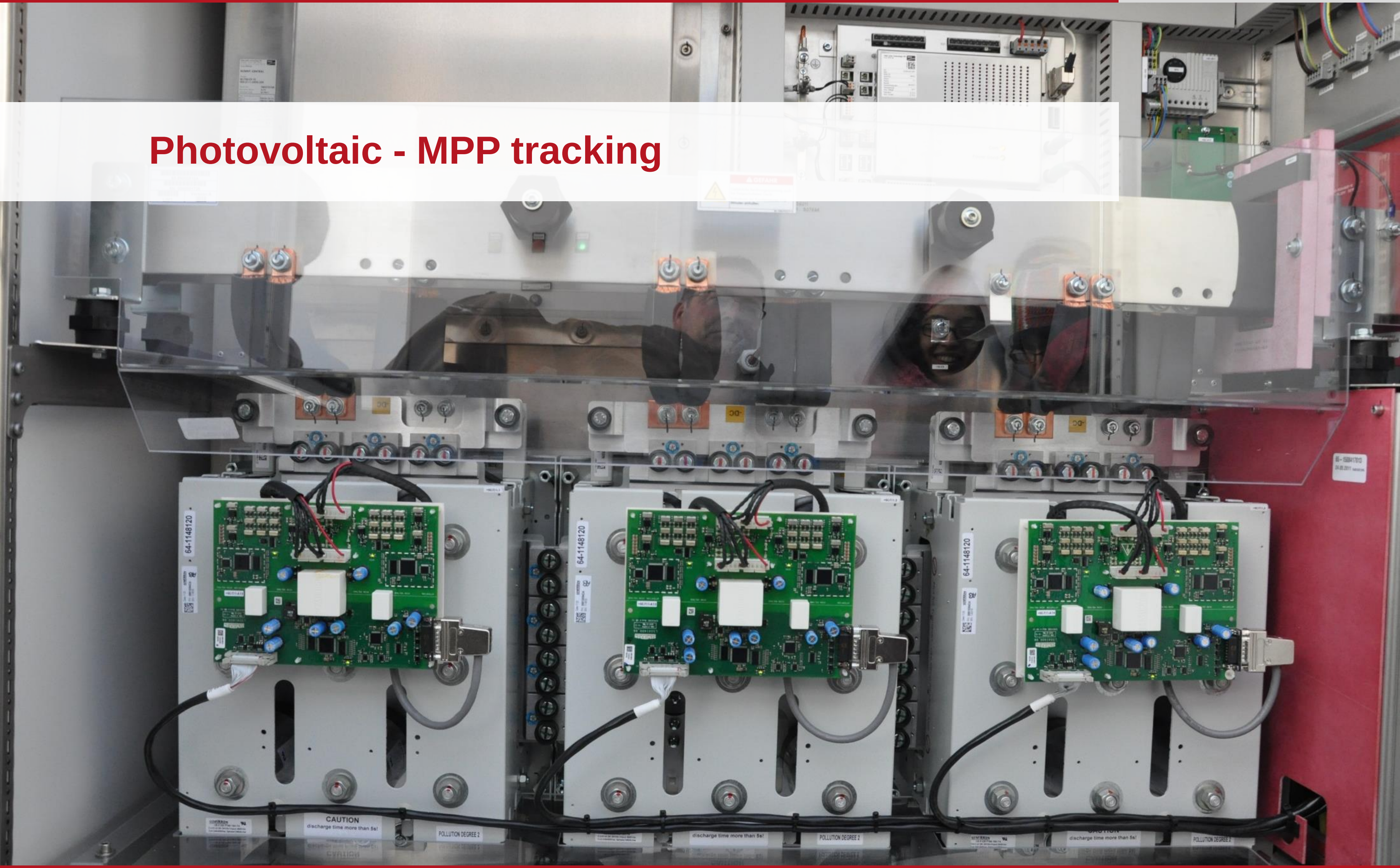
- The Market Data Register aims to improve the availability and quality of energy industry data.
- Registration is mandatory for **all** electricity and gas **generation** facilities that are or will be directly or indirectly connected to an electricity or gas grid.
- There is no minimum size requirement. **Consumption** facilities only have to be registered if they are connected to a high-voltage or extra-high-voltage grid or to a transmission grid.
- The registered data is publicly viewable, but personal data and location data of small plants (below 30 kWp) are not published. www.marktstammdatenregister.de

Market Data Register in Germany (slide in German)

MaStR-Nr. der Einheit	Anzeige-Name der Einheit	Betriebs-Status	Inbetriebnahmedatum der Einheit	Registrierungs m der Einheit
SEE935227660914	BHKW B-Gebäude	Dauerhaft stillgelegt	15.02.2012	26.05.2021
SEE943006430184	Hof Krone-Raue	In Betrieb	20.04.2006	26.05.2021
SEE920652594415	Aufdach	In Betrieb	12.05.2021	26.05.2021
SEE948668330889	Speicher	In Betrieb	12.05.2021	26.05.2021
SEE937453351468	PV Anlage Thomas Scharfenberger	In Betrieb	24.04.2021	26.05.2021
SEE951697010189	Speicher Thomas Scharfenberger	In Betrieb	25.05.2021	26.05.2021
SEE973303599932	ANDZIE2	In Betrieb	20.04.2021	26.05.2021
SEE956503492098	PV Frontor	In Betrieb	05.05.2021	26.05.2021

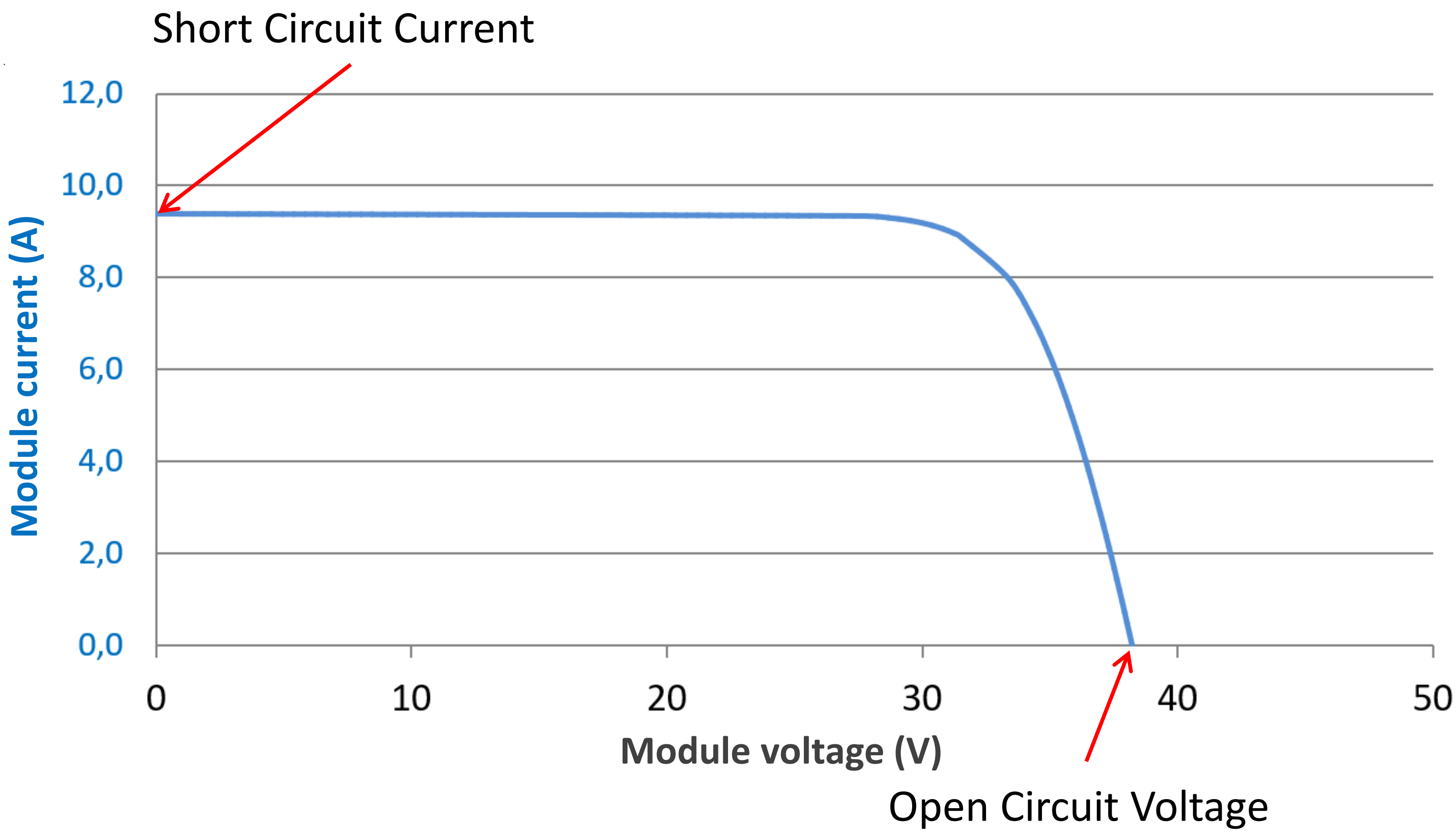
Source: https://www.marktstammdatenregister.de/MaStR/Einheit/Einheiten/OeffentlicheEinheitenuebersicht

Photovoltaic - MPP tracking



Modelling of the PV array performance

- I-V curve of Trina Allmax TSM-280 (I = Current, V = Voltage)



Exercise:
Maximum Power Point Tracking (MPPT)

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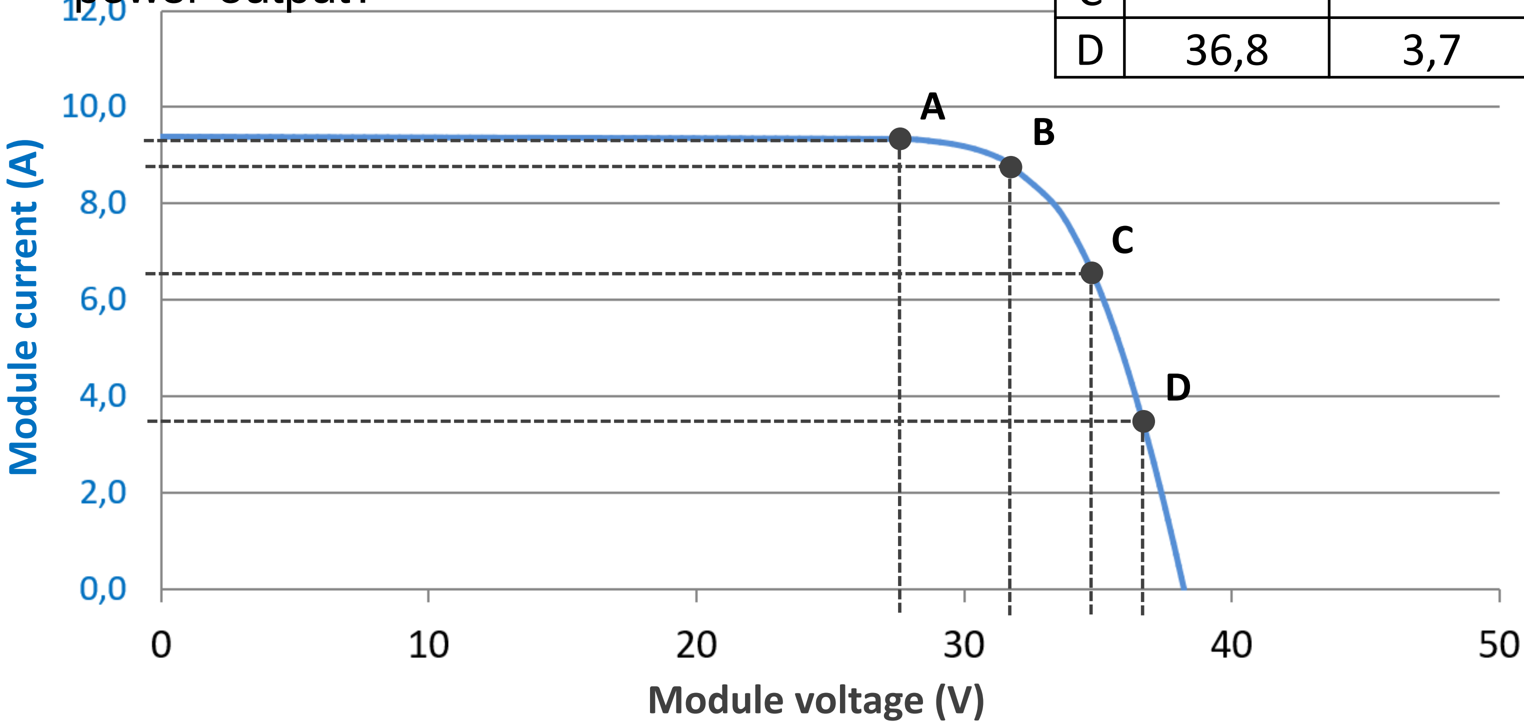
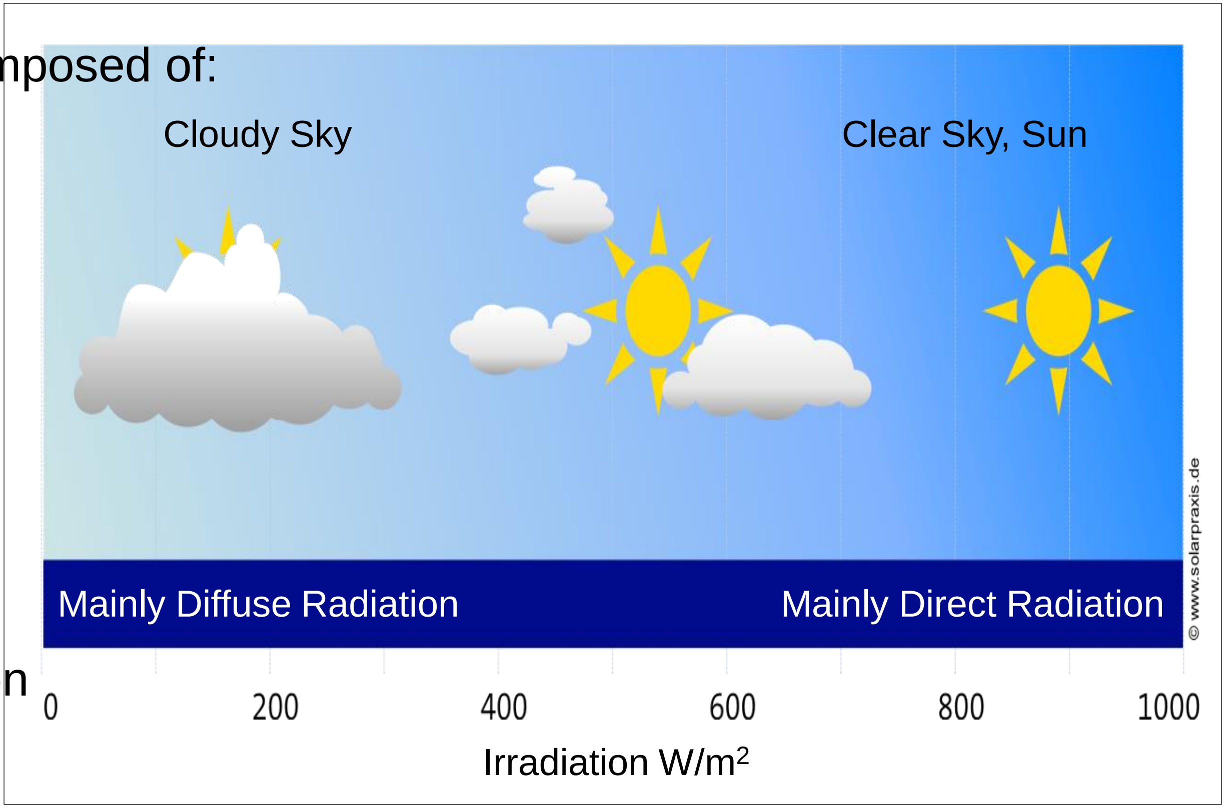
- Exercise: Please calculate the power output (P=V*I) in all four possible operating points (A, B, C, D). Which point has the highest power output?

	$V_{DC(V)}$	$I_{DC(A)}$	$P_{DC(W)}$
A			
B			
C			
D	36,8	3,7	136



Correlation of irradiation and weather

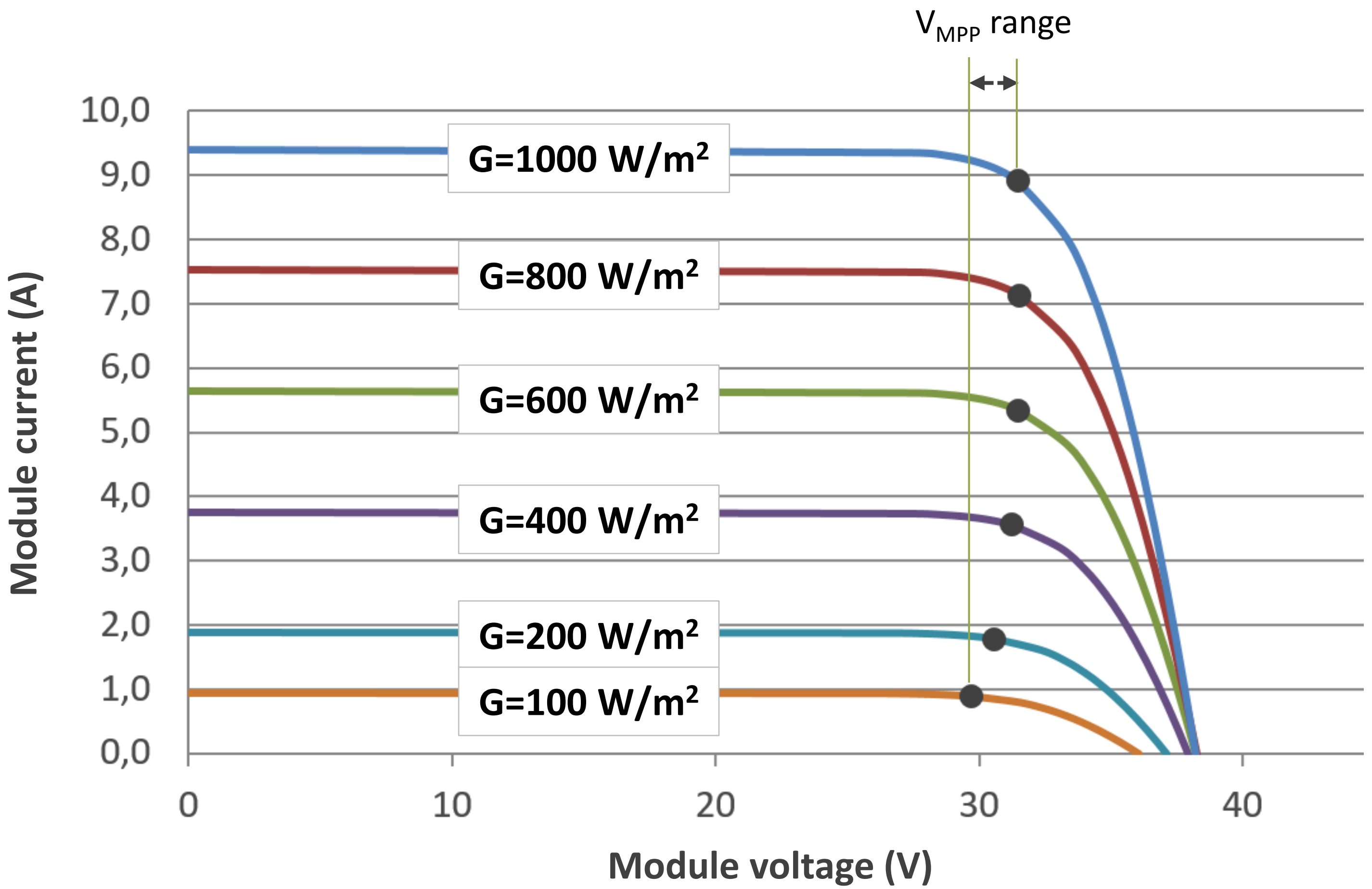
- Global radiation is composed of:
  - direct radiation (coming directly from sun, casting shadows)
  - Diffuse radiation (scattered, without clear direction) and
  - Reflected radiation



- Depending upon the cloud conditions and the time of the day, both
  - irradiation power and
  - proportion of direct and diffuse radiation can vary greatly

Effect of light intensity on the I-V Curve

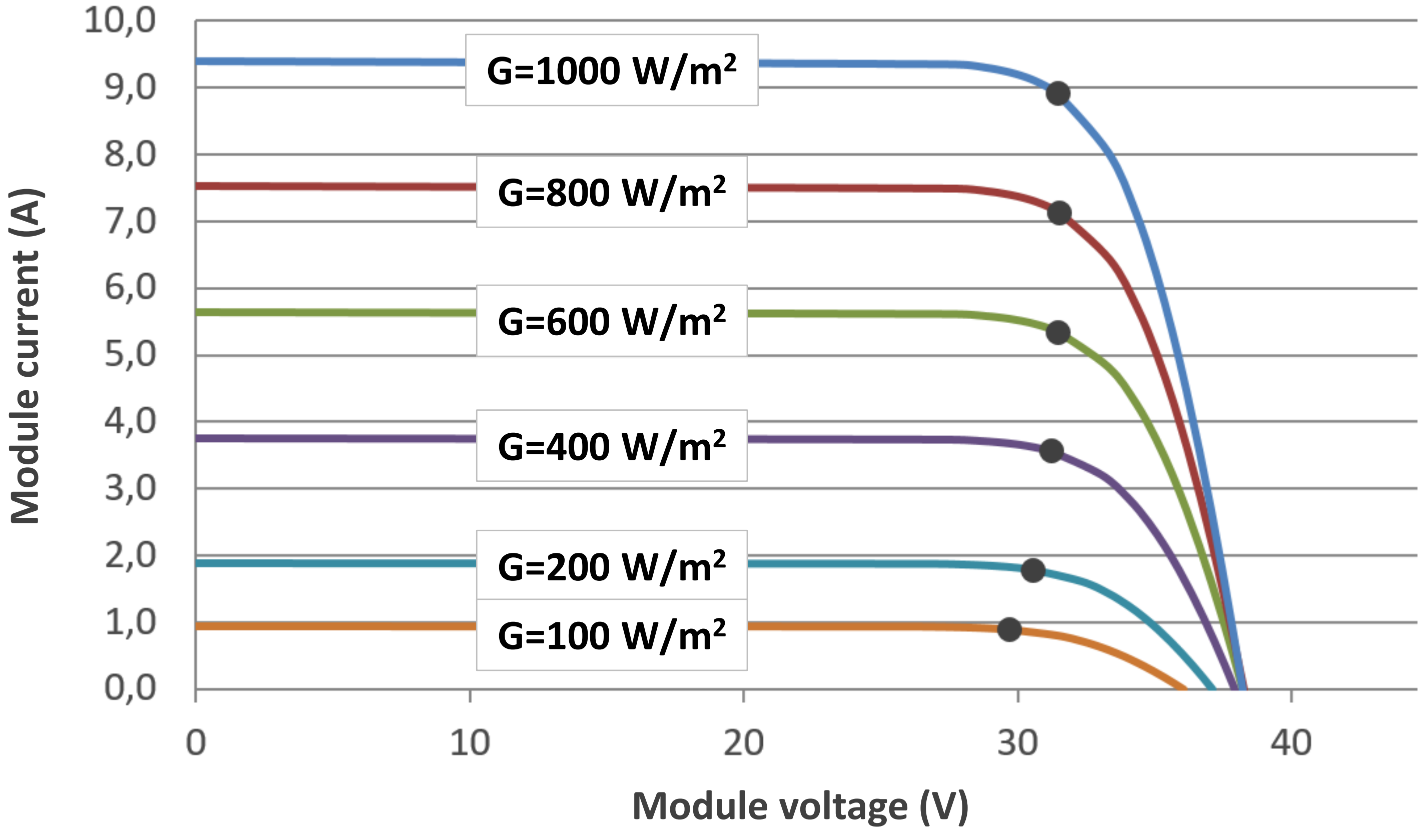
- Electrical parameters (I-V curve)
  - Trina Allmax TSM-280



Exercise:
Effect of light intensity on the I-V Curve

- Exercise:
  Please calculate the power output (P=V*I) for 1000 W/m² and 100 W/m².

	G (w/m²)	$V_{DC(V)}$	$I_{DC(A)}$	$P_{DC(W)}$
A	1000			
B	100			



Trina Allmax TSM-280

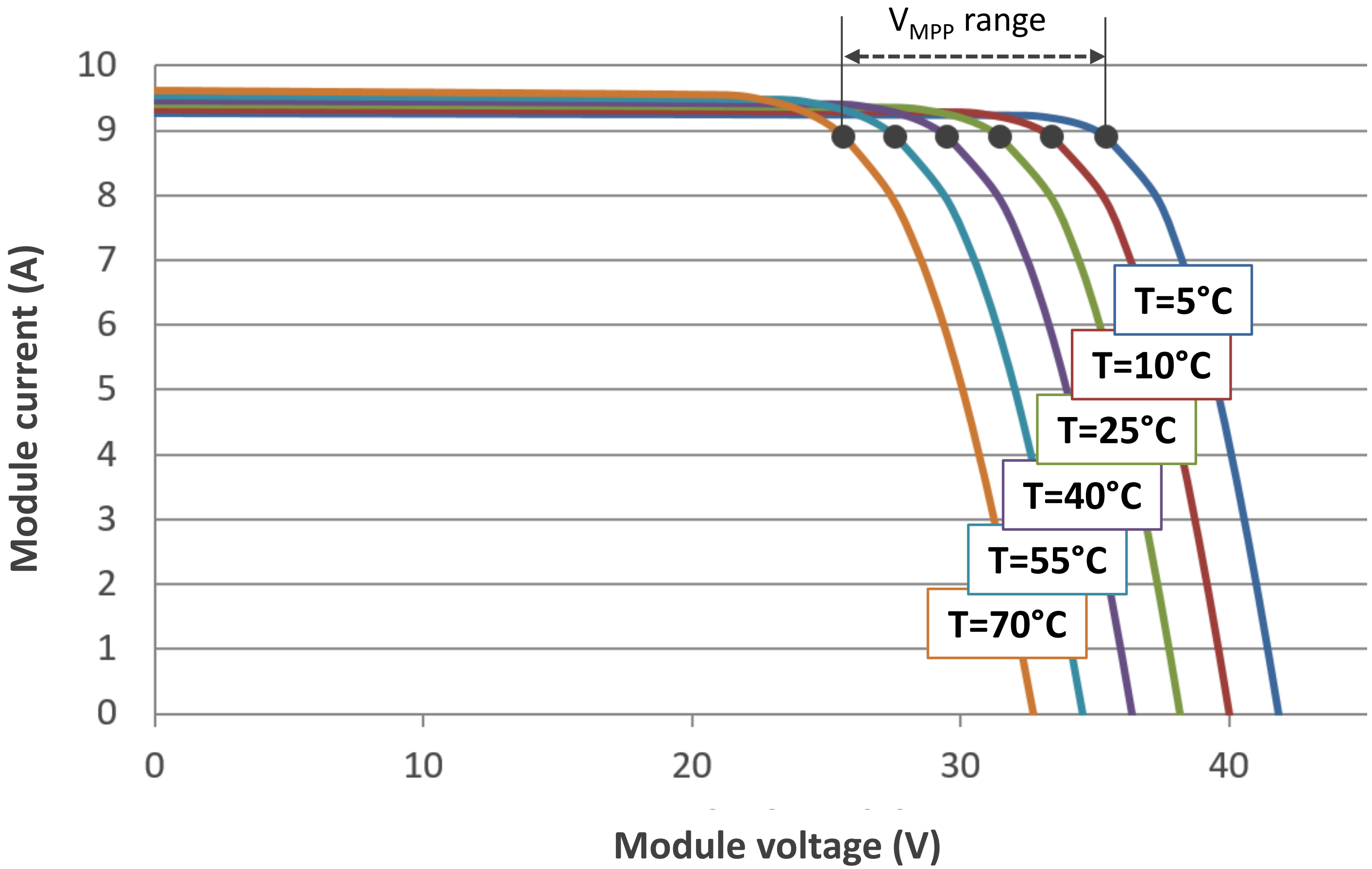
Effect of temperature on the power output of a module

- The operating temperature of the PV module has a great influence on the output power.
- Standard test condition is 25°C. Temperature can rise up to 85°C.
- A rise in temperature reduces the voltage and thus the output power.
- The operating temperature of the module is determined by the balance between
  - the radiation intensity,
  - the heat generated by the PV module,
  - the heat dissipated into the medium.

Source: Fraunhofer “Thermal Modelling of a PV module in operation and production”, 2019

Effect of temperature on the I-V Curve

- Electrical parameters
  - Trina Allmax TSM-280

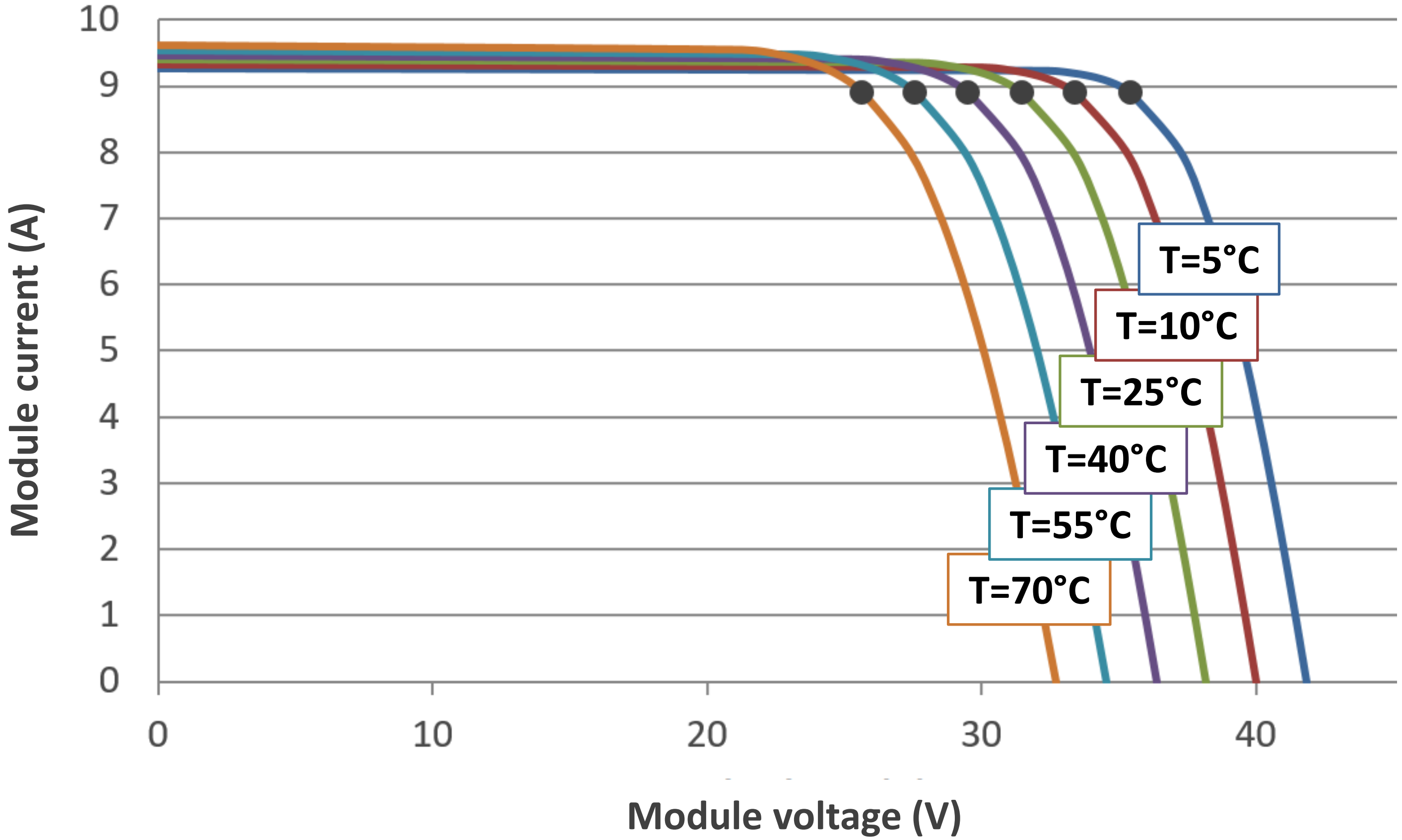


* Temperature effect on MPP current not considered in IV-curves.

Exercise:
Effect of temperature on the I-V Curve

- Exercise: Please calculate the power output (P=V*I) for a module temperature of 10°C and 70°C

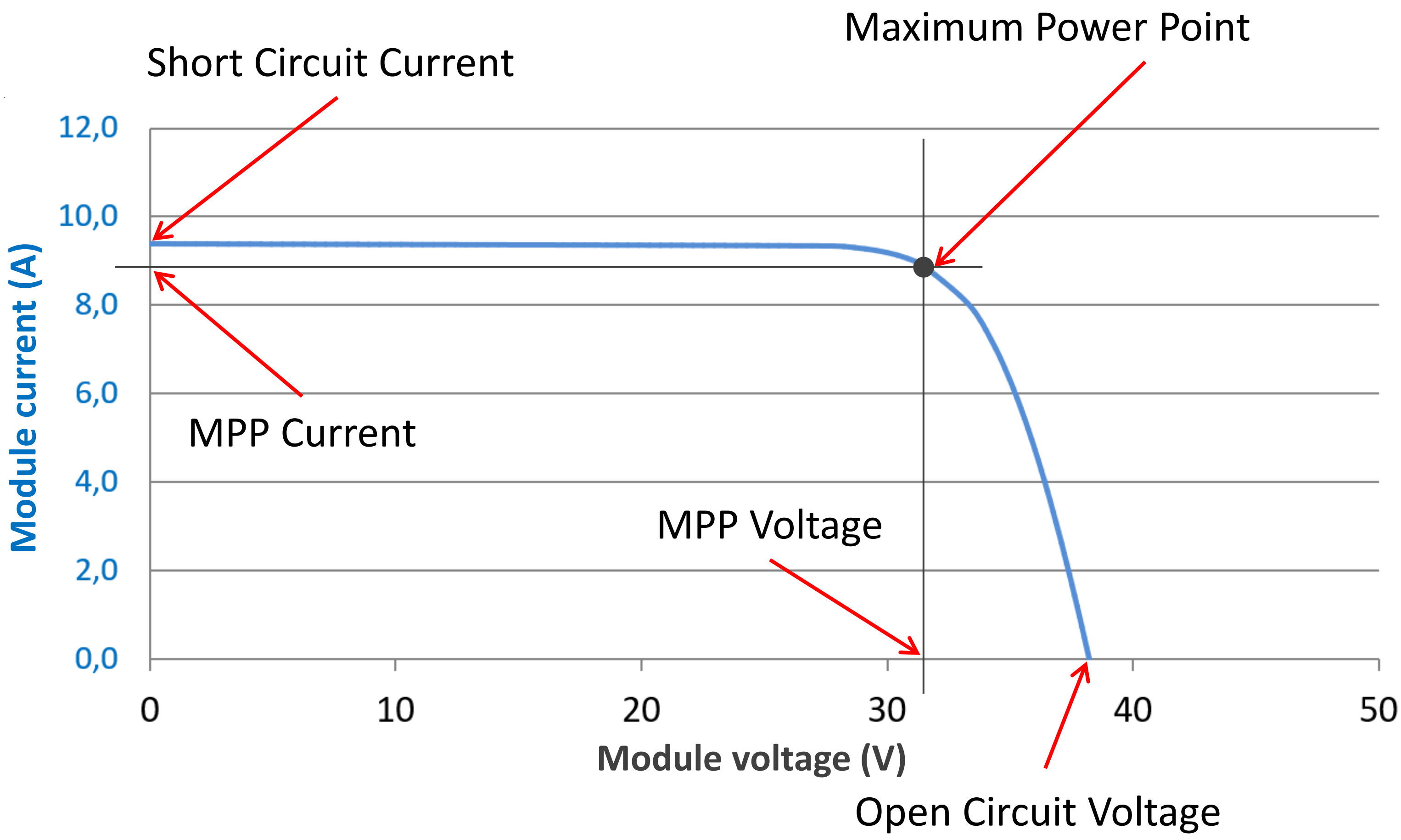
	T (°C)	$V_{DC(V)}$	$I^*_{DC(A)}$	$P_{DC(W)}$
A	10			
B	70			



Trina Allmax TSM-280

Modelling of the PV array performance

- I-V curve of Trina Allmax TSM-280



Modelling of the PV array performance

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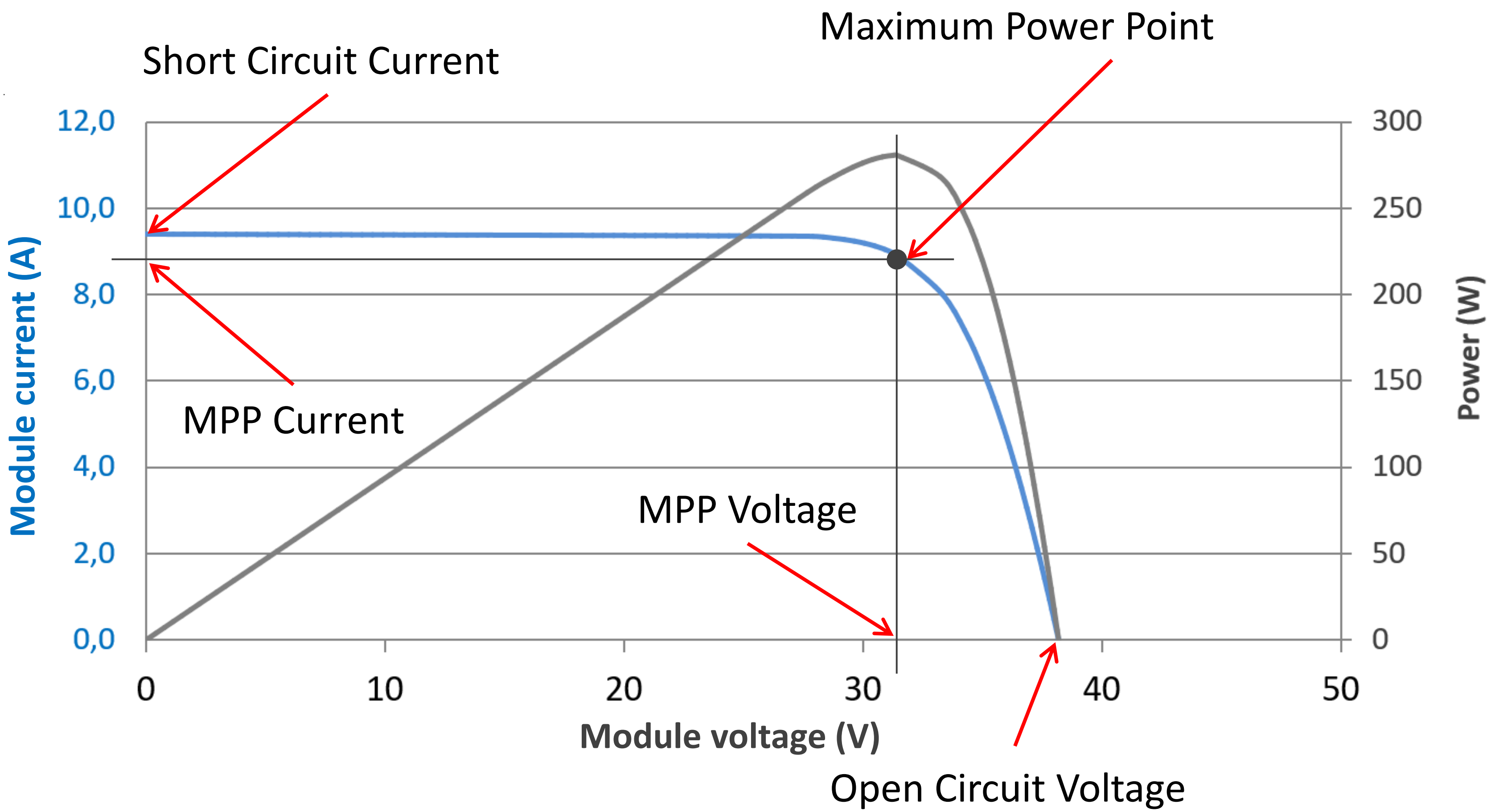

Exercise: Power output at different DC-Voltages

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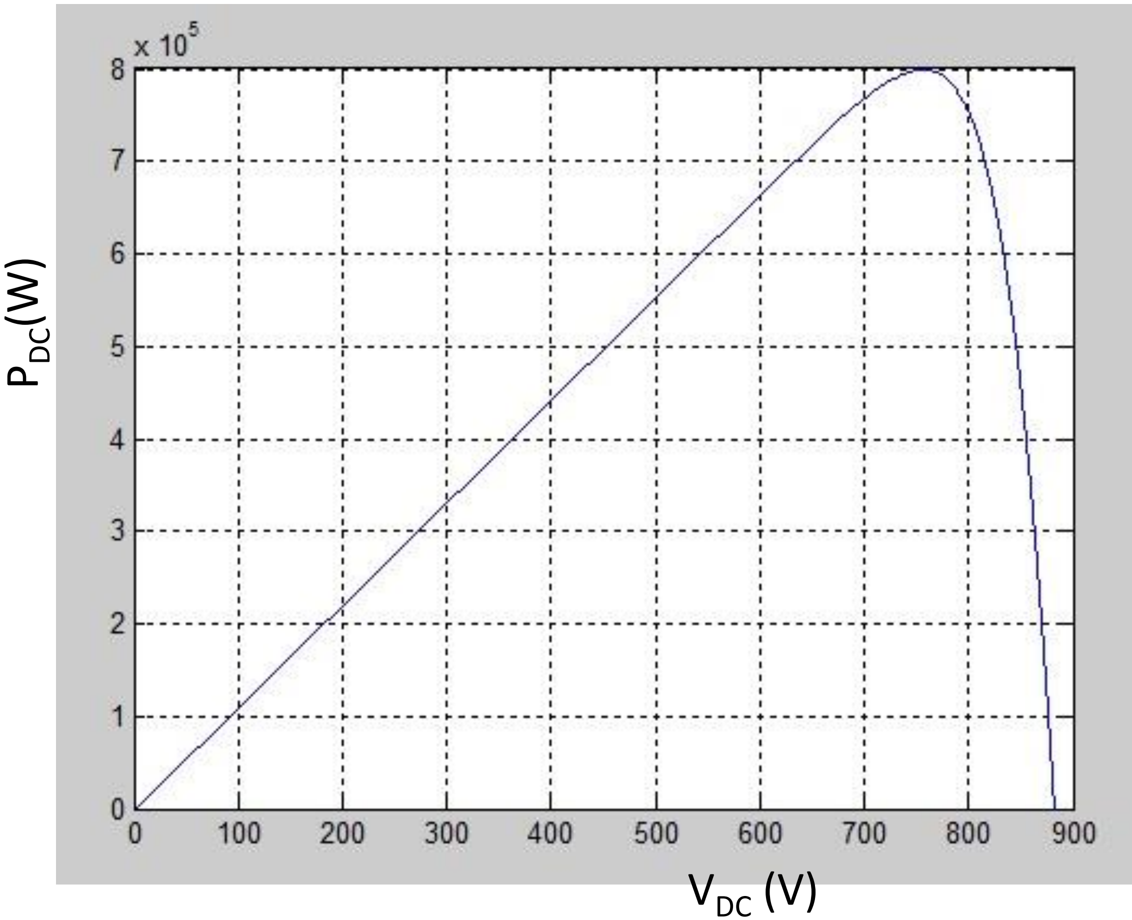
- Exercise: Please estimate the power output (P_{DC}) at a DC-Voltage (V_{DC}) of 400V, 600V and 750V.



V_{DC} (V)	P_{DC} (W)
400	
750	
850	

4 Frequency control

Balance between generation and load

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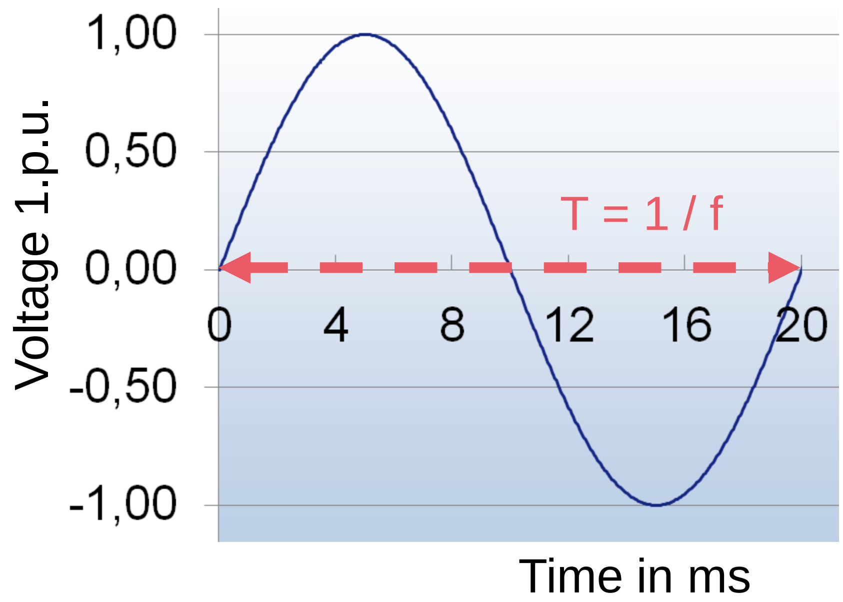
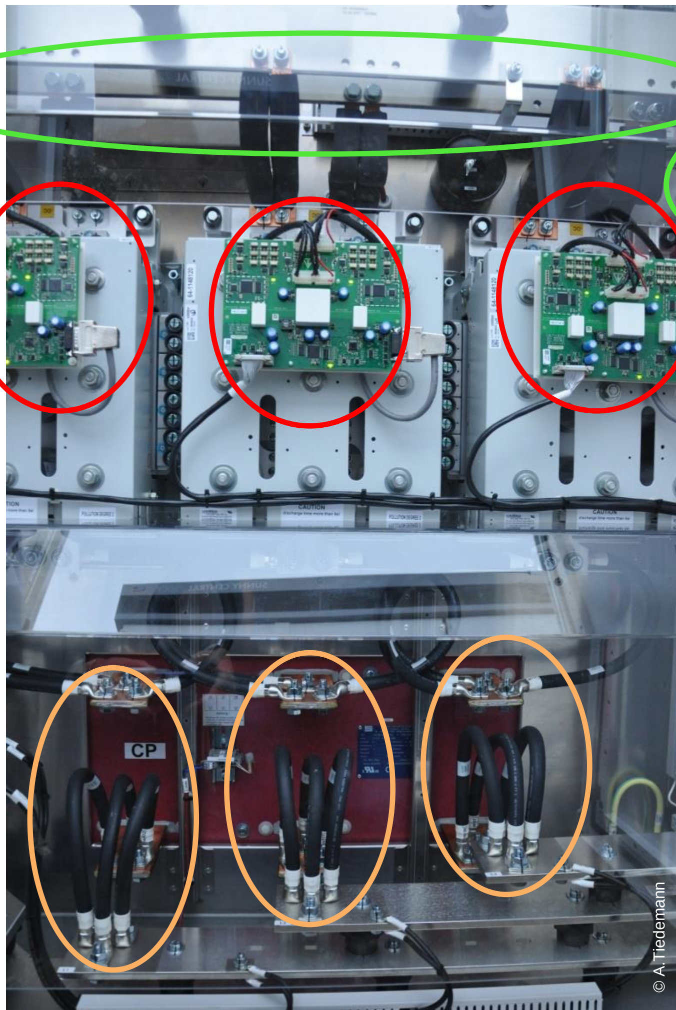
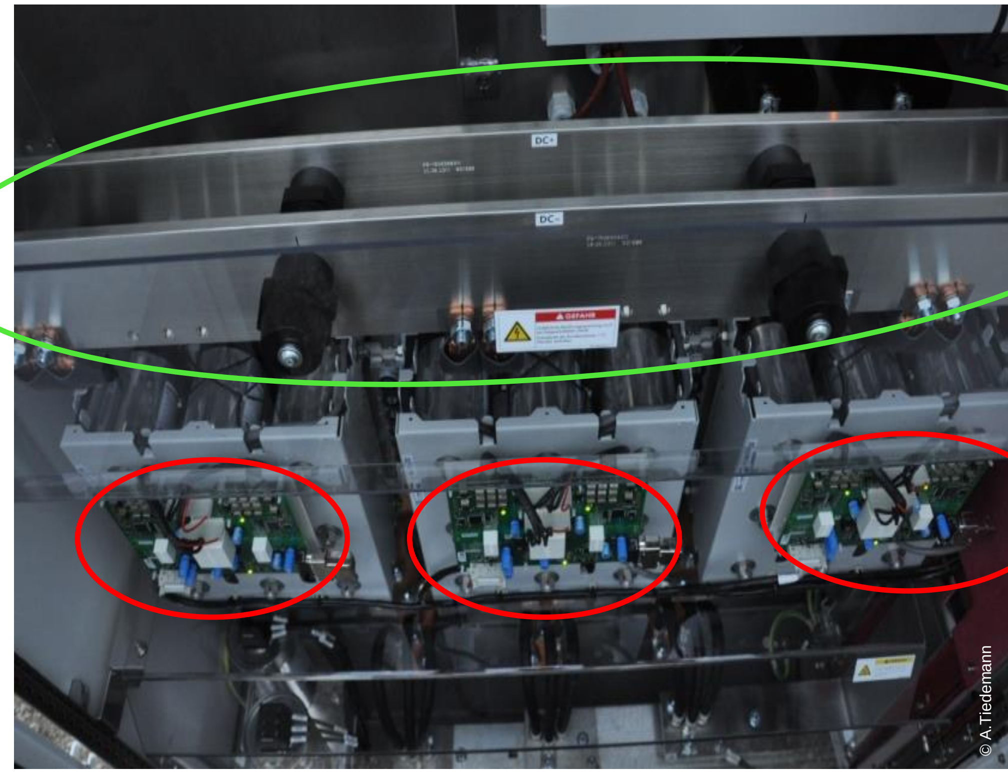
- Frequency is the number of occurrences of a repeating event per unit time
- Unit: Hertz, Hz = 1/s
- Frequency of voltage and current:
  - The number of times that the waveform of the voltage and the waveform of the current repeat per second.
  - The electrons in the circuit change their direction two times per Hz.
- In a 50 Hz system one wave lasts 20ms (T = 1000ms/50 = 20ms)



Central SMA inverter: Direct current (DC), IGBTs (insulated gate bipolar transistor) and alternating current (AC)





DC input to IGBT

IGBT (insulated-gate bipolar transistor)

AC output from IGBT

3 Phase converter design - from AC do DC

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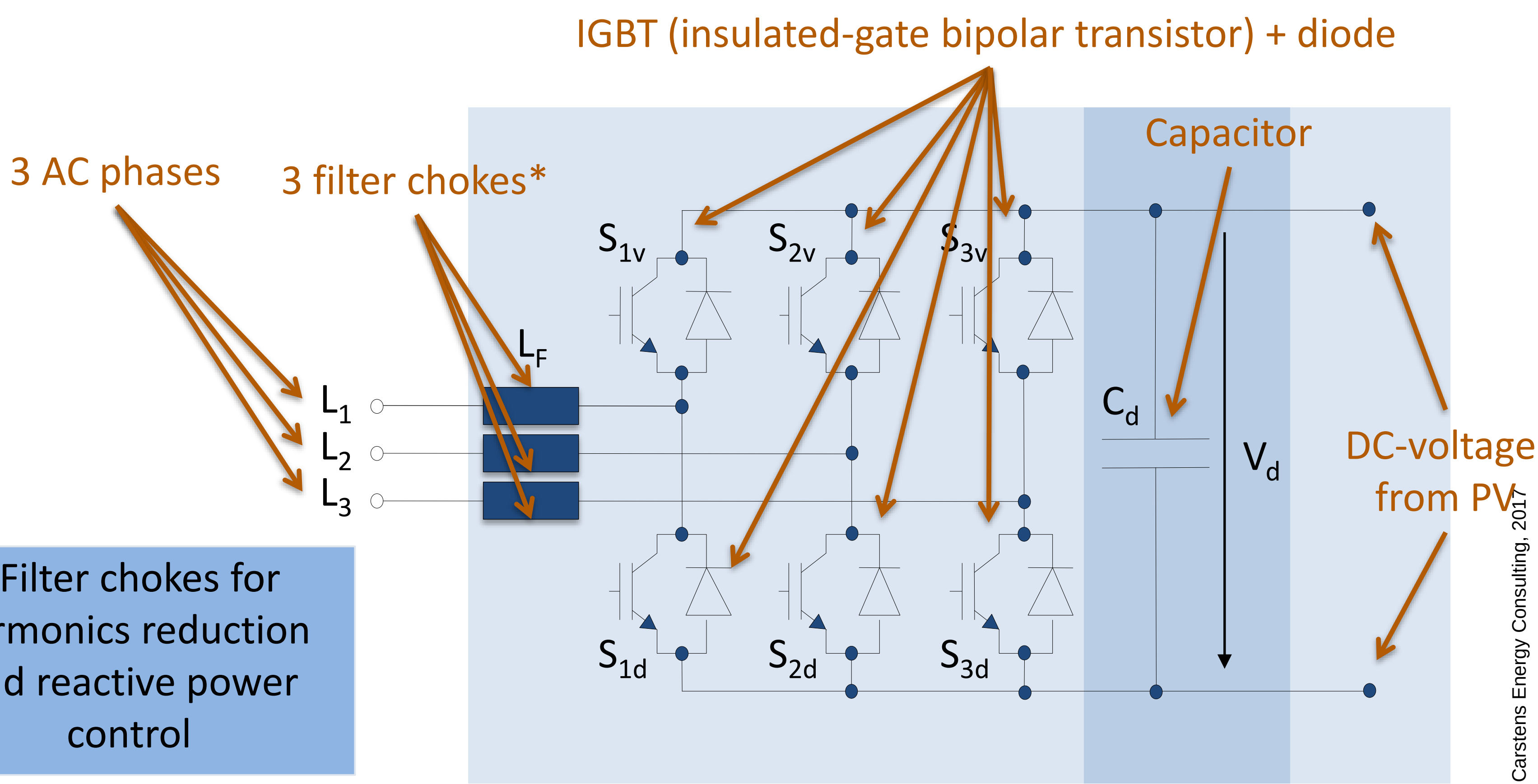

*Filter chokes for harmonics reduction and reactive power control

Converter AC Connection

Converter

Converter DC Connection

Source: CES Carstens Energy Consulting, 2017

Example 1 for status of switches to generate a voltage $+V_d$ between line 1 and line 2 ($V_{L1,L2} = +V_d$)

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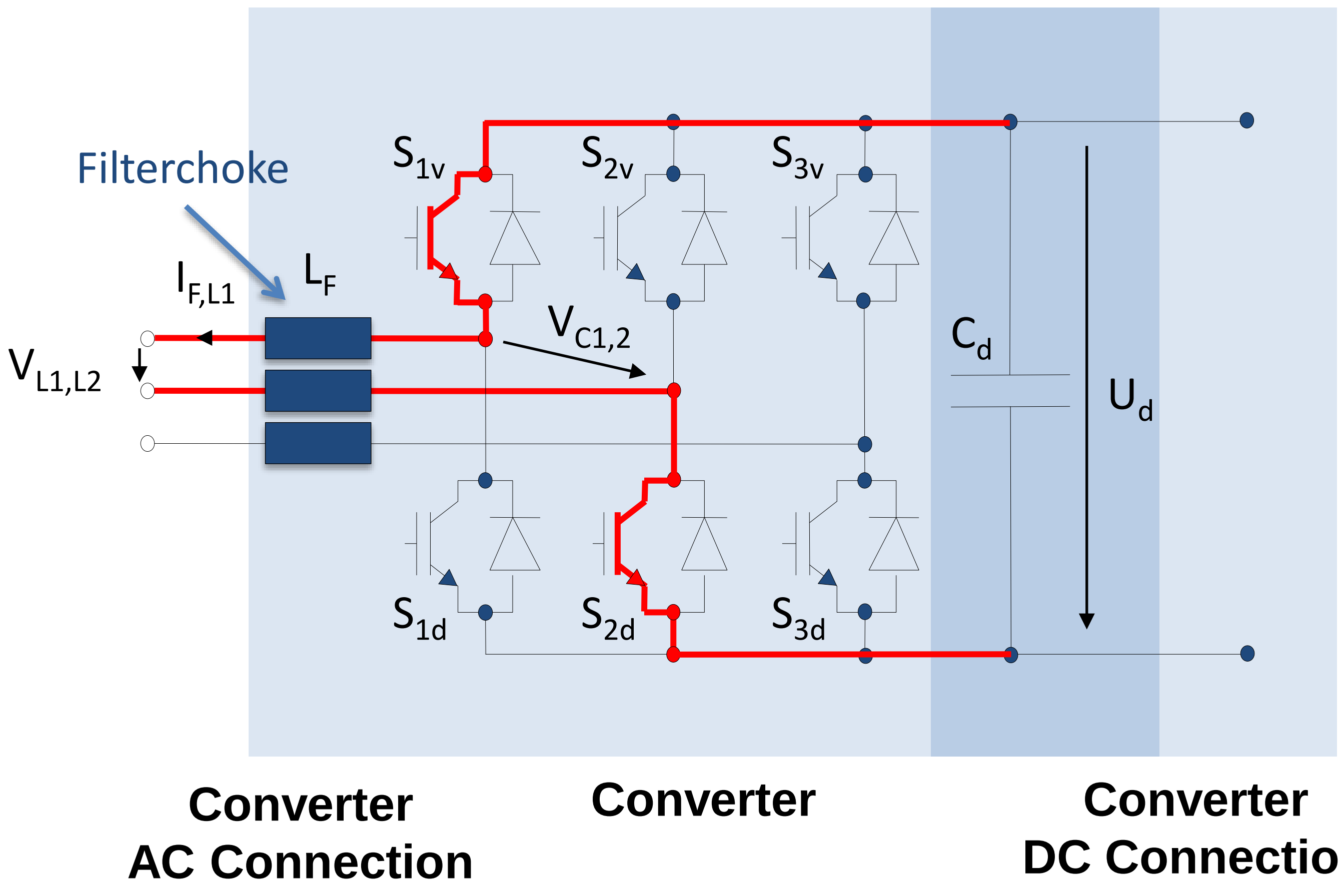
- Voltages deepening on switches status
- Voltage $V_{C1,2}$ can be $+V_d$, 0, $-V_d$
- Equivalent: $V_{C2,3}$ and $V_{C3,1}$
- S_{1v} and S_{2d} closed
- $V_{L1,L2} = +V_d$

Switch	Status
S1v	closed
S2v	open
S3v	open
S1d	open
S2d	open
S3d	closed

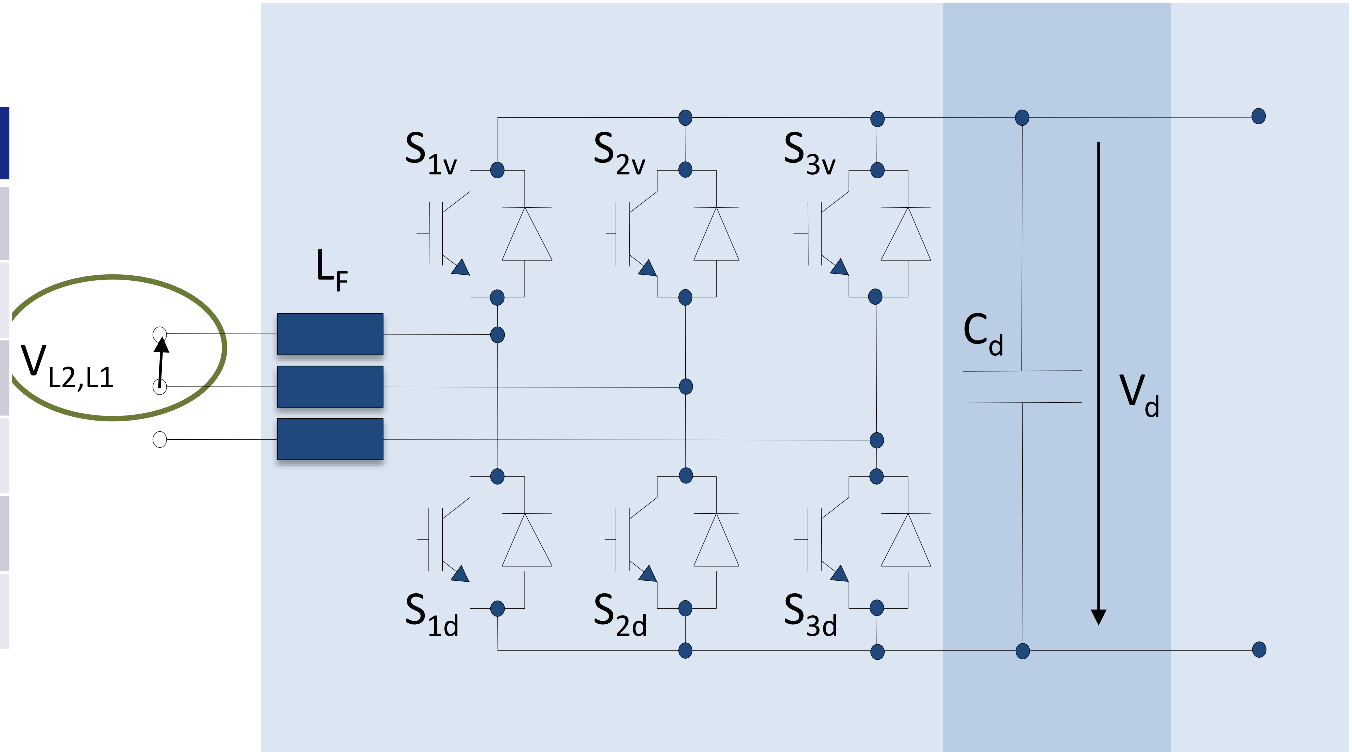


Source: CES Carstens Energy Consulting, 2017

Exercise: which IBGTs have to open and which have to close for a voltage of $V_{L2, L1}$

- $V_{L2,L1} = -V_d$

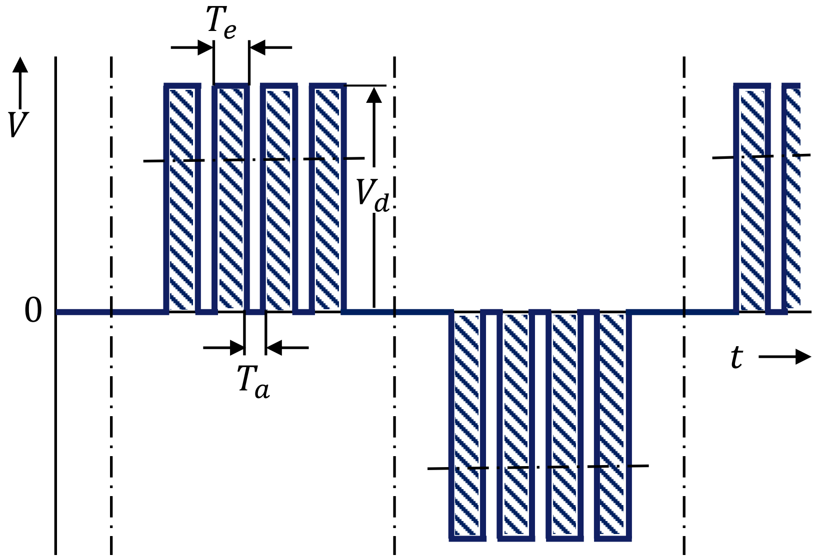
Switch	Status
S1v	
S2v	
S3v	
S1d	
S2d	
S3d	

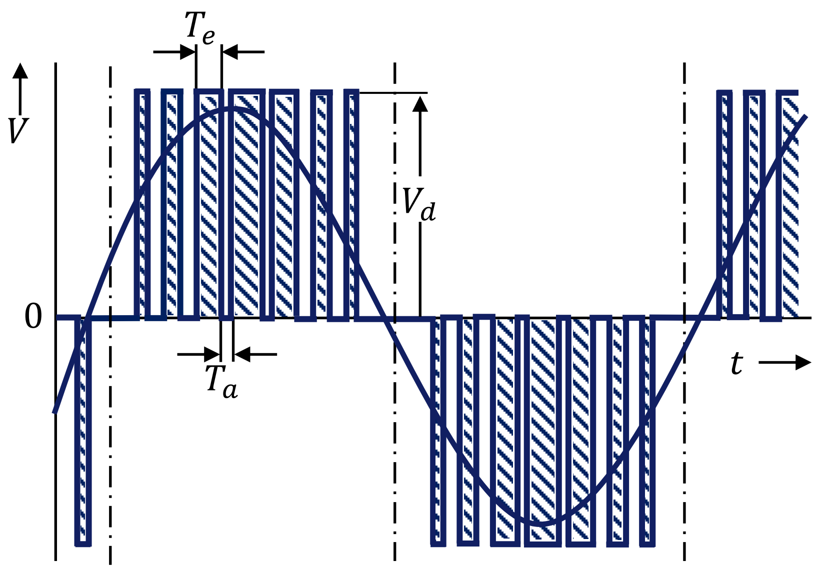


Converter AC Connection **Converter** **Converter DC Connection**

Source: CES Carstens Energy Consulting, 2017

Fundamental Voltage in PWM – from DC to AC





- Switched on: T_e
- Switched off: T_a
- $T_e + T_a = T$
- Rectangular voltage blocks with frequency 1/T

- Length of pulse changes voltage time area
- The longer switched on, the bigger voltage time area
- With pulse width modulation for every time step T effective voltage V_{C1} can be every voltage between $+V_d$ and $-V_d$
- Fundamental sinewave $V_{C,1}$ realizable

Source: Heumann: Grundlagen der Leistungselektronik
Source: CES Carstens Energy Consulting, 2017

Maximum thresholds of grid frequency for safe operation

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Deviation	Actions
0	Nominal frequency
> +/-20 mHz	Activation of primary control
> +/-50 mHz	Disturbed operation
> +/-180 mHz	Maximum quasi-steady-state frequency deviation
- 800 mHz	Minimum instantaneous frequency
> -1000 mHz	Load-shedding frequency criterion

Source: ENTSO

Grid code example: Behavior of PV in the event of over frequency

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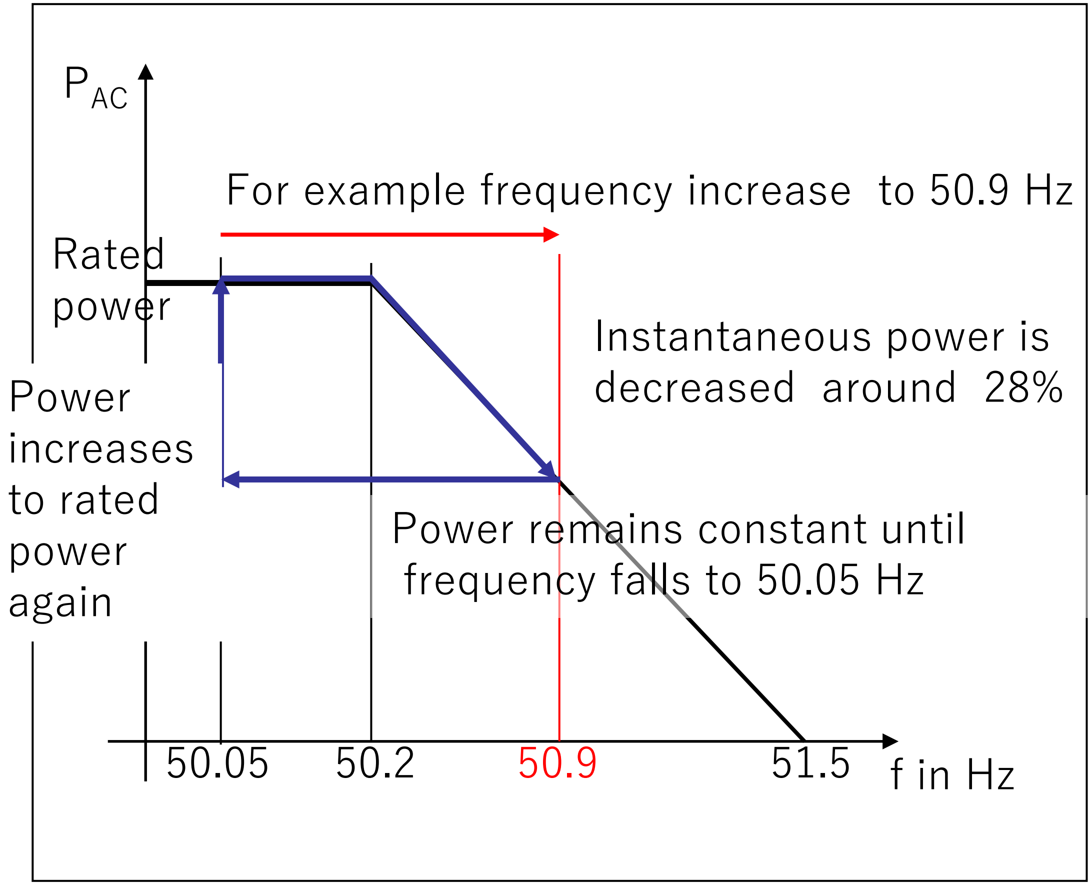

Requests

- Start of power reduction if frequency over 50.2 Hz
- Gradient: 40%

Exercise: PV overfrequency control strategy

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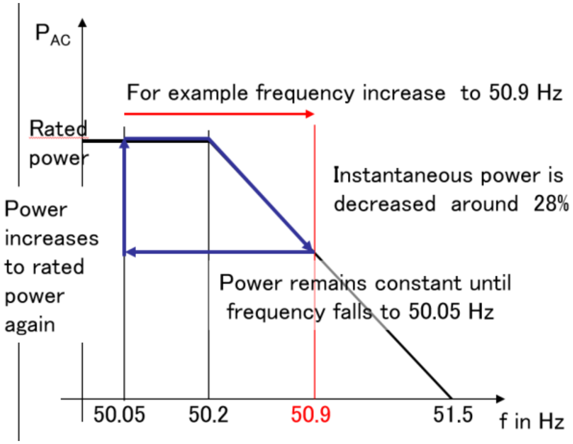
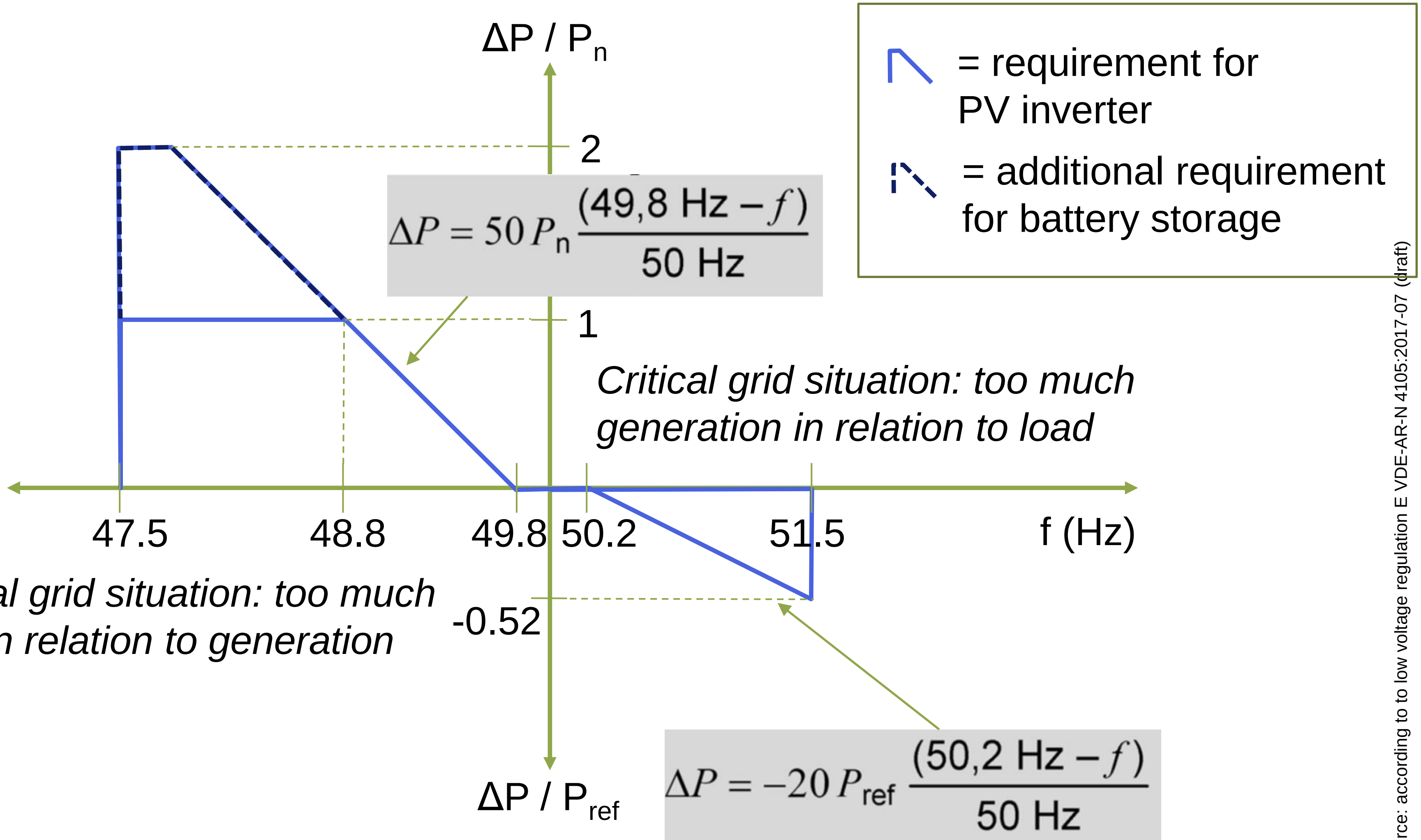
- Assume a PV farm measures the power supply system frequency at the grid connection point automatically. It controls the power output of the PV farm according to the over frequency control strategy presented in the previous slide. Assume the actual PV farm generates 1 MW.
- Exercise: Analyse the previous graph to calculate the power output of the PV farm at the following frequencies:



Power supply system Frequency (Hz)	PV farm power output (kW)
50.05	
50.2	
50.9	
51.5	

Active power requirements at over- and under frequency (underfrequency with storage)



$$\Delta P = 50\, P_n \frac{(49{,}8\ \text{Hz} - f)}{50\ \text{Hz}}$$

$$\Delta P = -20\, P_{ref} \frac{(50{,}2\ \text{Hz} - f)}{50\ \text{Hz}}$$

Critical grid situation: too much generation in relation to load

Critical grid situation: too much load in relation to generation

Source: according to to low voltage regulation E VDE-AR-N 4105:2017-07 (draft)

Example: Active power requirements at over- and under frequency – Example for Pref = 100 kW and PN = 200kW

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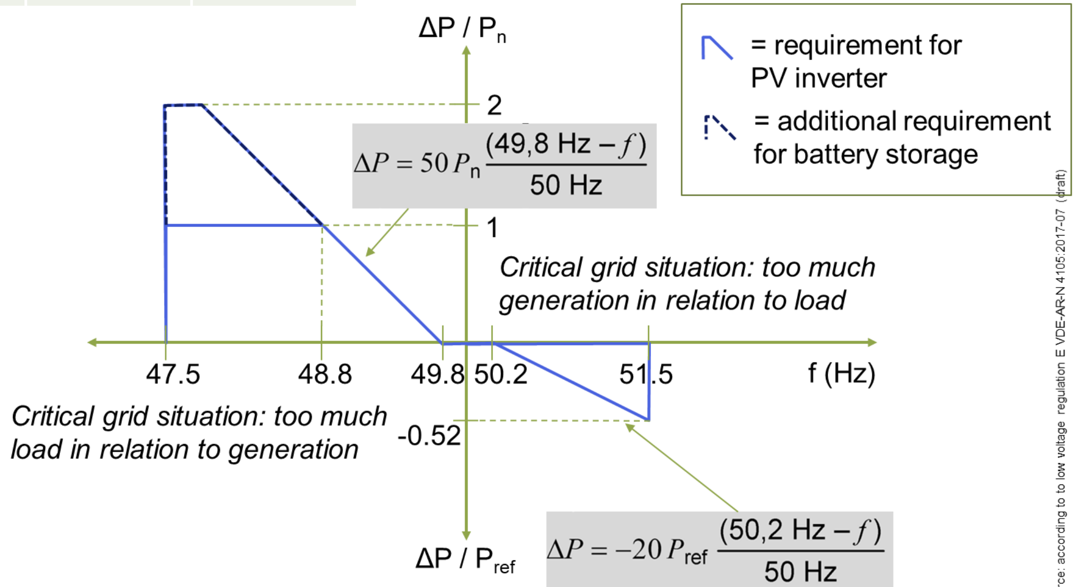
Overfrequency

f (Hz)	Pref (kW)	Δ P (kW)
50.2	100	0
50.3	100	4
50.4	100	8
50.5	100	12
50.6	100	16
50.7	100	20
50.8	100	24
50.9	100	28
51	100	32
51.1	100	36
51.2	100	40
51.3	100	44
51.4	100	48
51.5	100	52

Underfrequency

f (Hz)	PN (kW)	Δ P (kW)
49.8	200	0
49.6	200	40
49.4	200	80
49.2	200	120
49	200	160
48.8	200	200



Source: according to to low voltage regulation E VDE-AR-N 4105:2017-07 (draft)

Thank you!

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